Video Article

HKUST-1 as a Heterogeneous Catalyst for the Synthesis of Vanillin

Rebeca Yépez[1], Juan F. Illescas[1], Paulina Gijón[1], Manuel Sánchez-Sánchez[2], Eduardo González-Zamora[3], Rosa Santillan[4], J. Raziel Álvarez[5], Ilich A. Ibarra[5], Julia Aguilar-Pliego[1]

[1]Autonomous Metropolitan University-Azcapotzalco
[2]Institute of Catalysis and Petroleum Chemistry, ICP-CSIC
[3]Department of Chemistry, Autonomous Metropolitan University-Iztapalapa
[4]Department of Chemistry, Center of Investigation and Superior Studies (IPN)
[5]Research Institute of Material, National Autonomous University of Mexico

Correspondence to: Ilich A. Ibarra at argel@unam.mx

URL: http://www.jove.com/video/54054
DOI: doi:10.3791/54054

Keywords: Chemistry, Issue 113, Porous Coordination Polymers (PCPs), HKUST-1, heterogeneous catalysis, open metal sites, oxidation, trans-ferulic acid, vanillin

Date Published: 7/23/2016

Citation: Yépez, R., Illescas, J.F., Gijón, P., Sánchez-Sánchez, M., González-Zamora, E., Santillan, R., Álvarez, J.R., Ibarra, I.A., Aguilar-Pliego, J. HKUST-1 as a Heterogeneous Catalyst for the Synthesis of Vanillin. *J. Vis. Exp.* (113), e54054, doi:10.3791/54054 (2016).

Abstract

Vanillin (4-hydoxy-3-methoxybenzaldehyde) is the main component of the extract of vanilla bean. The natural vanilla scent is a mixture of approximately 200 different odorant compounds in addition to vanillin. The natural extraction of vanillin (from the orchid *Vanilla planifolia, Vanilla tahitiensis* and *Vanilla pompon*) represents only 1% of the worldwide production and since this process is expensive and very long, the rest of the production of vanillin is synthesized. Many biotechnological approaches can be used for the synthesis of vanillin from lignin, phenolic stilbenes, isoeugenol, eugenol, guaicol, *etc*., with the disadvantage of harming the environment since these processes use strong oxidizing agents and toxic solvents. Thus, eco-friendly alternatives on the production of vanillin are very desirable and thus, under current investigation. Porous coordination polymers (PCPs) are a new class of highly crystalline materials that recently have been used for catalysis. HKUST-1 ($Cu_3(BTC)_2(H_2O)_3$, BTC = 1,3,5-benzene-tricarboxylate) is a very well known PCP which has been extensively studied as a heterogeneous catalyst. Here, we report a synthetic strategy for the production of vanillin by the oxidation of *trans*-ferulic acid using HKUST-1 as a catalyst.

Video Link

The video component of this article can be found at http://www.jove.com/video/54054/

Introduction

The use of porous coordination polymers (PCPs) as heterogeneous catalysts[1-4] is a relatively new research field. Due to very interesting properties that PCPs show, *e.g.,* porous regularity, high surface area and metal access, they can offer new alternatives for heterogeneous catalysts[5-6]. The generation of catalytically active PCPs has been the main focus of many research groups[7-10]. A porous coordination polymer is constituted by metal ions and organic linkers and thus, the catalytic activity of these materials is provided by any of these parts. Some PCPs contain unsaturated (active) metals that can catalyze a chemical reaction[11]. However, the generation of unsaturated metal sites (open metal sites) within coordination polymers is not a trivial task and it represents a synthetic challenge that can be summarized in: (*i*) the generation of vacant coordination by removal of labile ligands[7-11]; (*ii*) the generation of bimetallic PCPs by incorporating organometallic ligands (previously synthesized)[8,12-13]; (*iii*) the post-synthetic variation of the metal ions[9,14-15] or to the organic ligands[10, 16-17] within the pores of the PCPs. Since the methodology (*i*) is the simplest thus, it is the most frequently used. Typically, the generation of open metal sites has been used for enhancing the affinity of PCPs towards H_2[18-19], as well as for designing active heterogeneous catalysts[20-27]. In order to achieve good catalyst properties, PCPs need to show, additionally to the accessibility of open metal sites, retention of the crystallinity after the catalytic experiment, relatively high thermal stability and chemical stability to the reaction conditions.

HKUST-1 ($Cu_3(BTC)_2(H_2O)_3$, BTC = 1,3,5-benzene-tricarboxylate)[7] is a well-investigated porous coordination polymer constructed with Cu(II) cations, that are coordinated to the carboxylate ligands and water. Interestingly, these water molecules can be eliminated (by heating) and this provides a square planar coordination around the copper ions which exhibit hard Lewis acid properties[11]. Bordiga and co-workers[28] showed that the elimination of these H_2O molecules did not affect the crystallinity (retention of the regularity) and the oxidation state of the metal ions (Cu(II)) was not affected. The use of HKUST-1 as a catalyst has been extensively investigated[29-33] and in particular (very relevant for the present work) the oxidation with hydrogen peroxide of aromatic molecules[34].

Vanilla is one of the most widely used flavoring agents in the cosmetic, pharmaceutical and food industries. It is extracted from the cured beans of the orchid *Vanilla planifolia, Vanilla tahitiensis* and *Vanilla pompon*. The Mayan and Aztec civilizations (pre-Columbian people) first realized the enormous potential of vanilla as a flavoring agent since it improved the chocolate flavor[35-37]. Vanilla was first isolated in 1858[38] and it was not until 1874[39] that the chemical structure of vanillin was finally determined. The natural extraction of vanillin (from the orchid *Vanilla planifolia, Vanilla tahitiensis* and *Vanilla pompon*) represents only 1% of the worldwide production and since this process is expensive and very long[40], the rest of vanillin is synthesized[40]. Many biotechnological approaches can be used for the synthesis of vanillin from lignin, phenolic stilbenes, isoeugenol, eugenol, guaicol, *etc.* However, these approaches have the disadvantage of harming the environment since these processes use strong oxidizing agents and toxic solvents[41-43]. Herein, we report a synthetic strategy for the production of vanillin by the oxidation of *trans*-ferulic acid using HKUST-1 as a catalyst.

Protocol

CAUTION: The chemicals used in this catalytic procedure are relatively low in toxicity and non-carcinogenic. Please use all appropriate safety precautions when performing this experimental procedure such as safety glasses, gloves, lab coat, full length pants and closed-toe shoes. One part of the following procedures involves standard air-free handling techniques.

1. Activation of the Catalyst (HKUST-1)

1. Crystallinity Characterization of the Catalyst
   Note: HKUST-1 is a commercially available porous coordination polymer (catalyst). In order to corroborate the crystallinity of the catalyst, samples of HKUST-1 need to be characterized by powder X-ray diffraction (PXRD).
    1. Collect a PXRD pattern of a 0.1 g sample of HKUST-1 (on a diffractometer operating at 160 W (40 kV, 40 mA)) for Cu-Kα_1 radiation (λ = 1.5406 Å) in Bragg-Brentano geometry. Record a PXRD pattern from 5° to 60° (2θ) in 0.02° steps and 1 sec counting time[44].

2. Desolvation of HKUST-1
    1. Weigh 0.05 g of the catalyst (HKUST-1).
    2. Clamp a 250 ml two-neck round-bottom flask to a stand and insert a magnetic stirring bar into the round-bottom flask.
    3. Attach a condenser to the round-bottom flask.
    4. Use some vacuum grease or Teflon tape between the joints of the flask and condenser in order to generate a perfect seal.
    5. Connect the condenser, from the top, to a vacuum pump (*via* a stopcock to a hose).
    6. Make sure that the vacuum generated by the pump is approximately 10^{-2} bar.
       Note: For convenience, this experimental set up (the two-neck round-bottom flask attached to a condenser, which is connected to a vacuum pump) will be referred as the activation system.
    7. Place the catalyst (0.05 g) inside the 250 ml two-neck round-bottom flask.
    8. Insert a rubber septum in the second neck of the round bottom flask and make sure that it seals (fits) properly.
    9. Carefully, place the activation system into a sand bath.
    10. Start the vacuum pump and carefully turn the stopcock until it is fully open. With a hot plate, heat the activation system up to 100 °C for 1 hr.
    11. Stir at the lowest speed of the hot plate, in order to distribute homogenously the catalyst at the bottom of the round-bottom flask.
    12. Turn off the heat (hot plate) after 1 hr of heating, and let the activation system cool to room temperature (under vacuum).
    13. Once the activation system has cooled down to room temperature, turn the stopcock off (thus, the activation system would be under passive vacuum) and turn the pump off.
    14. Connect a balloon filled with nitrogen (N_2), through the septum, to the two-neck round-bottom flask and wait a few seconds to reach the equilibrium pressure.
        Note: After the activation of the catalyst, leave it under an inert atmosphere (N_2) since the access to the uncoordinated metal sites (or open metal sites) is the key to obtain an active catalyst.
    15. Remove the balloon filled with N_2, when the equilibrium pressure has been achieved.
        Note: A color change from turquoise (as-received HKUST-1) to dark blue (upon activation) is observed.

2. Synthesis of Vanillin via Heterogeneous Catalysis

1. Degassing of the Organic Solvent
    1. Degas approximately 70 ml of ethanol by bubbling N_2 for 5 min.

2. Preparation of the Catalytic Reaction
    1. Add 10 ml of degassed ethanol to the two-neck round-bottom flask and gently stir the suspension on a hot plate.
    2. Add 5 ml of H_2O_2 (30 % in H_2O) to the suspension.
    3. Add 0.25 ml of acetonitrile to the suspension.
    4. Weigh 0.50 g of ferulic acid and dissolve it in 20 ml of degassed ethanol in a beaker.
    5. Add the dissolved ferulic acid to the suspension.
    6. Wash the beaker with 20 ml of degassed ethanol and add it to the suspension.

3. Oxidation of *Trans*-ferulic Acid to Vanillin
    1. Unplug the hose that connects the condenser to the vacuum pump.
    2. Turn on the tap water that goes through the condenser. Preferably, use a water pump.
    3. Heat the suspension up to 100 °C (refluxing) for 1 hr.
    4. Turn off the heat and stirring. Carefully lift the two-neck round-bottom flask (attached to the condenser) and let it cool to room temperature.

4. Work-up of the Reaction
    1. Filter off the reaction mixture (use a Buchner funnel and flask), recover the catalyst (HKUST-1) and wash it with 200 ml of ethyl acetate.

    Note: In order to speed up the filtration process, use a vacuum (connected to the Buchner flask) to quickly recover and wash the catalyst.
  2. Corroborate the retention of framework crystallinity of the catalyst by PXRD as in Section 1.
  3. Concentrate the combined organic phases (under vacuum with a rotary evaporator) and re-dissolve it with 100 ml ethyl acetate.
  4. Wash the organic phases (use a separation funnel) with a saturated solution of NH_4Cl (30 ml).
  5. Recover the organic phases and mix them with anhydrous Na_2SO_4 (30 g). Let the suspension stand for 15 min.
  6. Filter the suspension off and recover the filtrate.
  7. Concentrate the filtrate (to approximately 20 ml) under vacuum with a rotary evaporator.

5. Purification of the Residue (Vanillin)
  1. Purify the residue by flash column chromatography[44]. The stationary phase is silica gel and the mobile phase is a solvent mixture of ethyl acetate-hexane (5:95).
  2. Pack the glass column for chromatography (1 cm x 30 cm) with silica gel (1 cm x 6 cm). Saturate the column with acetate-hexane (5:95) solvent mixture.
  3. Pour carefully the concentrated-filtrate at top of the glass column.
  4. Slowly add the solvent mixture to the glass column and collect all of the fractions until 1,200 ml are collected.
  5. Concentrate the organic fractions (1,200 ml) with a rotary evaporator until dryness.
  6. Recover the final solid powder that is the purified vanillin.

Representative Results

Three representative samples of HKUST-1 were analyzed by infrared spectroscopy: non-activated, activated at 100 °C for 1 hr in an oven (exposed to air), and activated under vacuum (10^{-2} bar) at 100 °C for 1 hr. Thus, Fourier transform infrared (FTIR) spectra were recorded using a spectrometer with a single reflection diamond ATR accessory (**Figure 1**). For all spectra, 64 scans in the 4,000 to 400 cm^{-1} range were recorded with a spectral resolution of 4 cm^{-1}.

In order to confirm the composition of purified product from oxidation of *trans*-ferulic acid using HKUST-1 as a catalyst, a ^1H-NMR spectra was performed on a NMR spectrometer under a static magnetic field of 11.74 T at 25 °C (**Figure 2**). For that, a 5 mg sample was introduced into NMR test tube and 0.5 ml of deuterated chloroform ($CDCl_3$) was added.

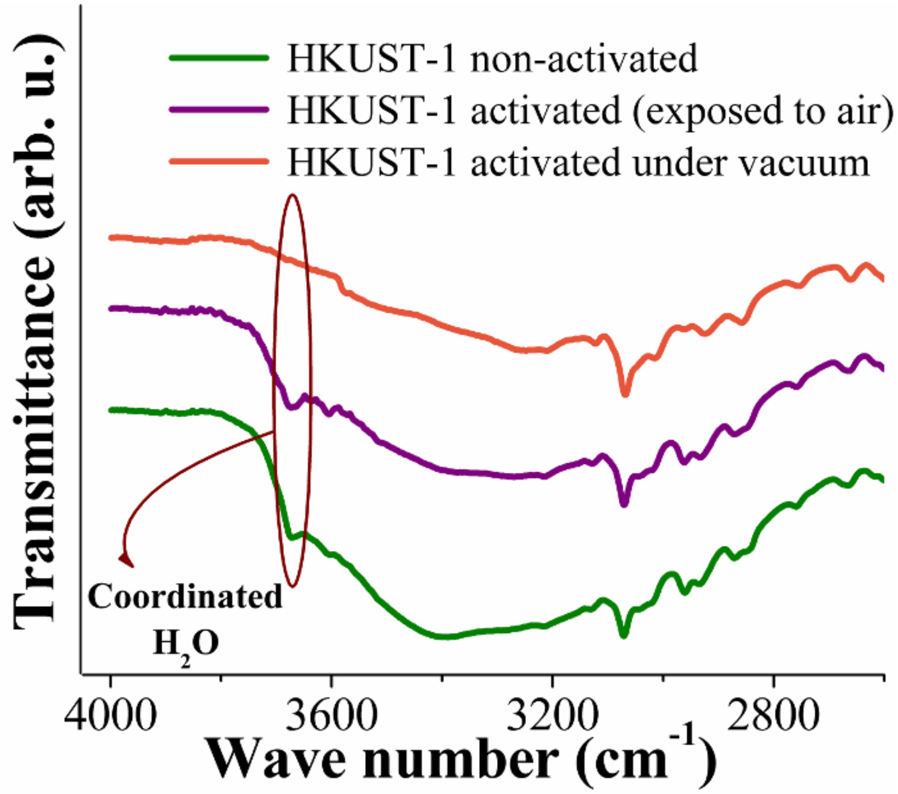

Figure 1: FTIR spectra of the catalyst (HKUST-1) at 25 °C. Non-activated (green line), activated in a conventional oven (purple line) and activated under vacuum (orange line). Reproduced from reference[44] with permission from the Centre National de la Recherche Scientifique (CNRS) and the Royal Society of Chemistry. Please click here to view a larger version of this figure.

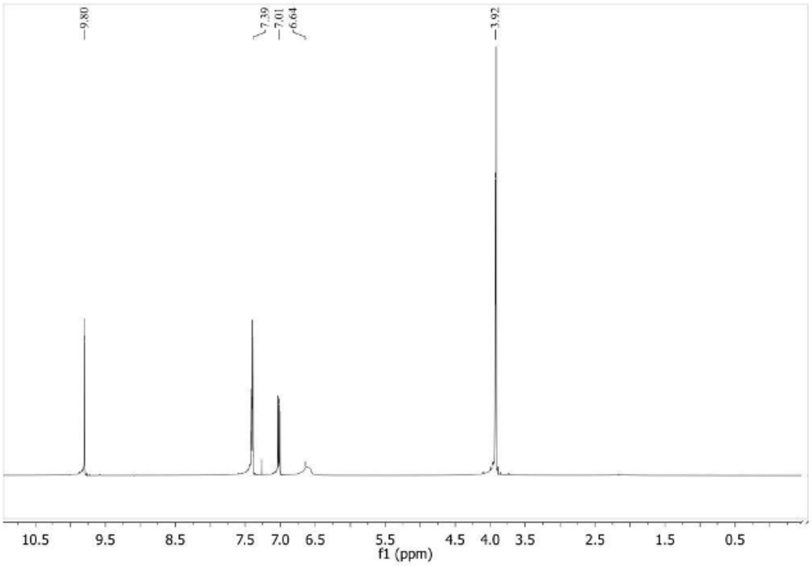

Figure 2: ^{1}H-NMR spectra of vanillin after column chromatography purification on silica gel when the catalyst (HKUST-1) was activated under vacuum (10^{-5} bar) and 100 °C for 1 hr.

Discussion

The fundamental step for the catalytic conversion of *trans*-ferulic acid to vanillin was the activation of the catalyst (HKUST-1). If the catalyst is not activated *in situ* (under vacuum and at 100 °C), only partial conversion of *trans*-ferulic acid to vanillin was observed[44]. In other words, the accessibility to open metal sites is crucial for the catalytic cycle[44], and this can be achieved by the elimination of coordinated water to the Cu(II) metal sites within the porous coordination polymer.

Therefore, in order to investigate this phenomenon three infrared experiments were carried out. The first experiment, the FTIR spectrum of a non-activated sample of HKUST-1 (**Figure 1**) showed the characteristic absorption bands at 3,400 cm^{-1} and 3,680 cm^{-1} corresponding to uncoordinated water (broad absorption band) and coordinated water (sharp absorption band), respectively. Second, the HKUST-1 sample activated in a conventional oven (exposed to air) showed a FTIR spectrum with minimal changes in comparison to the previous experiment: a decrease in the intensity of the absorption band at 3,400 cm^{-1} but no change on the sharp absorption band at 3,680 cm^{-1} (**Figure 1**). This change suggested an incomplete loss of uncoordinated water and the maintenance of coordinated water to the Cu(II) metal ion. Finally, the FTIR spectrum of the catalyst activated *in situ* exhibited two major changes (respect to the non-activated catalyst), a considerable reduction in the intensity of the absorption band at 3,400 cm^{-1} and a complete lost on the intensity of the absorption band at 3,680 cm^{-1}. Thus, when the catalyst is activated under vacuum (10^{-2} bar) and at 100 °C, it is possible to get complete access to the Cu(II) open metal sites; the elimination of any water molecules (non and coordinated) inside the pores of HKUST-1.

Once the catalytic reaction is finished, the catalyst can be easily recovered by filtration and re-used (**Figure 2**)[44]. Of course, it has to be re-activated (under vacuum, 10^{-2} bar, and at 100 °C). In order to facilitate the re-activation process, once the catalyst is recovered, washing it up with approximately 200 ml of ethyl acetate is needed. Then, the catalyst can be left at room temperature (on the Buchner funnel) for 30 min, recovered and finally transferred into the activation system (*vide supra)*.

The scaling up of the reaction is the current limitation of this experimental technique. The maximum amount of catalyst used was 0.05 g which resulted in a conversion yield of 95% (obtained after isolation of the vanillin by flash column chromatography)[44]. This catalytic reaction was carried out with higher quantities of catalyst (consequently, more ferulic acid and the rest of the chemicals) and the conversion yield dropped down significantly.

Only the combination of activated heterogeneous catalyst with hydrogen peroxide is needed to catalyze the oxidation of *trans*-ferulic acid. In order to discriminate the heterogeneous catalytic conversion, blank tests (one without HKUST-1 and another without H_2O_2) were performed[44]. After these reactions were completed, in the same conditions, the analysis of product composition did not show the presence of vanillin[44].

The catalytic methodology presented in here showed how the heterogeneous catalyst (HKUST-1) can be used for the effective conversion of *trans*-ferulic acid to vanillin when it is activated *in situ*. Additionally the retention of the crystallinity of the catalyst was corroborated by PXRD[44] after this was re-used. Previous synthetic vanillin methodologies use strong oxidizing agents and toxic solvents[41-43]. The current methodology completely avoids these hazards and it also offers the ability to re-use the heterogeneous catalyst (HKUST-1).

Finally, we are investigating the applicability of the catalytic technique for the oxidation of different α,β-unsaturated carboxylic acids.

Disclosures

The authors have nothing to disclose.

Acknowledgements

The authors thank Dr. A. Tejeda-Cruz (X-ray; IIM-UNAM). R.Y. thanks CINVESTAV, Mexico for technical support. M.S.S acknowledges the financial support by Spanish Government, MINECO (MAT2012-31127). I.A.I thanks CONACyT (212318) and PAPIIT UNAM (IN100415), Mexico for financial support. E.G-Z. thanks CONACyT (156801 and 236879), Mexico for financial support. Thanks to U. Winnberg (ITAM and ITESM) for scientific discussions.

References

1. Corma, A., García, H., Llabrés i Xamena, F. X. Engineering Metal Organic Frameworks for Heterogeneous Catalysis. *Chem. Rev.* **110** (8), 4606-4655 (2010).
2. Gascon, J., Corma, A., Kapteijn, F., Llabrés i Xamena, F. X. Metal Organic Framework Catalysis: *Quo vadis*? *ACS Catal.* **4** (2), 361-378 (2014).
3. Ranocchiari, M., van Bokhoven, J. A. Catalysis by metal-organic frameworks: fundamentals and opportunities. *Phys. Chem. Chem. Phys.* **13**, 6388-6392 (2011).
4. Dhakshinamoorthy, A., Alvaro, M., Garcia, H. Commercial metal-organic frameworks as heterogeneous catalysts. *Chem. Commu.* **48** (92), 11275- 11288 (2012).
5. Corma, A., García, H. Lewis Acids as Catalysts in Oxidation Reactions: From Homogeneous to Heterogeneous Systems. *Chem. Rev.* **102** (10), 3837-3892 (2002).
6. Corma, A., García,*H. Lewis Acids: From Conventional Homogeneous to Green Homogeneous and Heterogeneous Catalysis. Chem. Rev.* **103** (11), 4307-4366 (2003).
7. Chui, S. S. Y., Lo, S. M. F., Charmant, J. P. H., Orpen, A. G., Williams, I. D. A Chemically Functionalizable Nanoporous Material $[Cu_3(TMA)_2(H_2O)_3]_n$. *Science.* **283** (5405), 1148-1150 (1999).
8. Farha, O. K., Shultz, A. M., Sarjeant, A. A., Nguyen, S. T., Hupp, J. T. Active-Site-Accessible, Porphyrinic Metal−Organic Framework Materials. *J. Am. Chem. Soc.* **133** (15), 5652-5655 (2011).
9. Zhang, J.-P., Horike, S., Kitagawa, S.*A Flexible Porous Coordination Polymer Functionalized by Unsaturated Metal Clusters. Angew. Chem. Int. Ed.* **46** (6), 889-892 (2007).
10. Wang, Z., Cohen, S. M. Postsynthetic modification of metal-organic frameworks. *Chem. Soc. Rev.* **38** (5), 1315-1329 (2009).
11. Llabres i Xamena, F. X., Luz, J., & Cirujano, F. G. Strategies for Creating Active Sites in MOFs. In: *Metal organic frameworks as heterogeneous catalysts.* Llabres i Xamena, F. X., Gascon, J., eds., Chapter 7 (2013).
12. Cho, S.-H., Ma, B., Nguyen, S. T., Hupp, J. T., Albrecht-Schmitt, T. E. A metal-organic framework material that functions as an enantioselective catalyst for olefin epoxidation. *Chem. Commun.* (24), 2563-2565 (2006).
13. Xie, M.-H., Yang, X.-L., Wu, C.-D. A metalloporphyrin functionalized metal-organic framework for selective oxidization of styrene. *Chem. Commun.* **47** (19), 5521-5523 (2011).
14. Zhang, X., Llabrés i Xamena, F. X., Corma, A. Gold(III) - metal organic framework bridges the gap between homogeneous and heterogeneous gold catalysts. *J. Catal.* **265** (2), 155-160 (2009).
15. Bohnsack, A. M., Ibarra, I. A., Bakhmutov, V. I., Lynch, V. M., Humphrey, S. M. Rational Design of Porous Coordination Polymers Based on Bis(phosphine)MCl_2 Complexes That Exhibit High-Temperature H_2 Sorption and Chemical Reactivity. *J. Am. Chem. Soc.* **135** (43), 16038-16041 (2013).
16. Ingleson, M. J., Perez-Barrio, J., Guilbaud, J.-B., Khimyak, Y. Z., Rosseinsky, M. J. Framework functionalisation triggers metal complex binding. *Chem. Commun.* (23),2680-2682 (2008).
17. Burrows, A. D., Frost, C. G., Mahon, M. F., Richardson, C. Post-Synthetic Modification of Tagged Metal-Organic Frameworks. *Angew. Chem. Int. Ed.* **47** (44), 8482-8486 (2008).
18. Dincă, M., Long, J. R. Hydrogen Storage in Microporous Metal-Organic Frameworks with Exposed Metal Sites. *Angew. Chem. Int. Ed.* **47** (36), 6766- 6779 (2008).
19. Ibarra, I. A., *et al.* Structures and H_2 Adsorption Properties of Porous Scandium Metal-Organic Frameworks. *Chem. Eur. J.* **16** (46), 13671-13679 (2010).
20. Gustafsson, M., *et al.* A Family of Highly Stable Lanthanide Metal−Organic Frameworks: Structural Evolution and Catalytic Activity. *Chem. Mater.* **22** (11), 3316-3322 (2010).
21. Mitchell, L., *et al.* Remarkable Lewis acid catalytic performance of the scandium trimesate metal organic framework MIL-100(Sc) for C-C and CN bond-forming reactions. *Catal. Sci. Technol.* **3** (3), 606-617 (2013).
22. Jeong, K. S., *et al.* Asymmetric catalytic reactions by NbO-type chiral metal-organic frameworks. *Chem. Sci.* **2** (5), 877-882 (2011).
23. Henschel, A., Gedrich, K., Kraehnert, R., Kaskel, S. Catalytic properties of MIL-101. *Chem. Commun.* (35), 4192-4194 (2008).
24. Dhakshinamoorthy, A., *et al.* Iron(III) metal-organic frameworks as solid Lewis acids for the isomerization of α-pinene oxide. *Catal. Sci. Techol.* **2** (2), 324-330 (2012).
25. Kurfiřtová, L., Seo, Y.-K., Hwang, Y. K., Chang, J.-S., Čejka, J. High activity of iron containing metal-organic-framework in acylation of *p*-xylene with benzoyl chloride. *Catal. Today.* **179** (1), 85-90 (2012).
26. Beier, M. J., *et al.* Aerobic Epoxidation of Olefins Catalyzed by the Cobalt-Based Metal-Organic Framework STA-12(Co). *Chem. Eur. J.* **18** (3), 887-898 (2012).
27. Ruano, D., Díaz-García, M., Alfayate, A., Sánchez-Sánchez, M. Nanocrystalline M-MOF-74 as Heterogeneous Catalysts in the Oxidation of Cyclohexene: Correlation of the Activity and Redox Potential. *Chem. Cat. Chem.* **7** (4), 674-681 (2015).
28. Prestipino, C., *et al.* Local Structure of Framework Cu(II) in HKUST-1 Metallorganic Framework:Spectroscopic Characterization upon Activation and Interaction with Adsorbates. *Chem. Mater.* **18** (5), 1337-1346 (2006).
29. Opanasenko, M., *et al.* Comparison of the catalytic activity of MOFs and zeolites in Knoevenagel condensation. *Catal. Sci. Technol.* **3** (2), 500-507 (2013).
30. Pérez-Mayoral, E., *et al.* Synthesis of quinolines *via* Friedländer reaction catalyzed by CuBTC metal-organic-framework. *Dalton Trans.* **41** (14), 4036-4044 (2012).

31. Schlichte, K., Kratzke, T., Kaskel, S. Improved synthesis, thermal stability and catalytic properties of the metal-organic framework compound $Cu_3(BTC)_2$. *Micropor. Mesopor. Mater.* **73** (1-2), 81-88 (2004).
32. Addis, D., *et al.* Hydrosilylation of Ketones: From Metal-Organic Frameworks to Simple Base Catalysts. *Chem. Asian J.* **5** (11), 2341-2345 (2010).
33. Wu, Y., *et al.* Kinetics of oxidation of hydroquinone to *p*-benzoquinone catalyzed by microporous metal-organic frameworks $M_3(BTC)_2$ [M = copper(II), cobalt(II), or nickel(II); BTC = benzene-1,3,5-tricarboxylate] using molecular oxygen. *Transition Met. Chem.* **34** (3), 263-268 (2009).
34. Marx, S., Kleist, W., Baiker, A. Synthesis, structural properties, and catalytic behavior of Cu-BTC and mixed-linker Cu-BTC-PyDC in the oxidation of benzene derivatives. *J. Catal.* **281** (1), 76-87 (2011).
35. May, P., Cotton, S. *Molecules That Amaze Us.* CRC Press, p.193 (2015).
36. Havkin-Frenkel, D., Belanger, F. C. *Handbook of Vanilla Science and Technology.* Wiley-BlackWell, p.3 (2011).
37. Zhao, S., *et al.* Preparation of ferulic acid from corn bran: Its improved extraction and purification by membrane separation. *Food Bioprocess Technol.* **92** (3), 309-313 (2014).
38. Gobley, T. W. Recherche sur le principe odorant de la vanilla. *J. Pharm. Chem.* **3**, 401, (1858).
39. Tiemann, F., Haarmann, W. Uber das coniferin und seine Umwandlung in das aromatisches princip der vanilla. *Ber. Dtsch. Chem. Ges.* **7** (1), 608-623 (1874).
40. Dignum, M. J. W., Kerler, J., Verpoorte, R. Vanilla production: technological, chemical, and biosynthetic aspects. *Food. Rev. Int.* **17** (2), 199-219 (2001).
41. Walton, N. J., Mayer, M. J., Narbad, A. Vanillin. *Phytochemistry.* **63** (5), 505-515 (2003).
42. Serra, S., Fuganti, C., Brenna, E. Biocatalytic preparation of natural flavours and fragrances. *Trends Biotechnol.* **23** (4), 193-198 (2005).
43. Longo, M. A., Sanromán, M. A. Production of Food Aroma Compounds: Microbial and Enzymatic Methodologies. *Food Technol. Biotechnol.* **44** (3), 335-353, (2006).
44. Yepez, R., *et al.* Catalytic activity of HKUST-1 in the oxidation of *trans*-ferulic acid to vanillin. *New. J. Chem.,* **39** (7), 5112-5115 (2015).